Transformer Coupling

Transformer Coupling Effects

In VIC circuits, the primary (L1) and secondary (L2) chokes may be magnetically coupled, either intentionally (bifilar winding) or unintentionally (proximity). This coupling significantly affects circuit behavior and must be understood for accurate analysis.

Magnetic Coupling Fundamentals

When two inductors share magnetic flux, they become coupled:

Mutual Inductance:

```
M = k × ?(L? × L?)
```

Where k is the coupling coefficient (0 ≤ k ≤ 1)

Coupling Coefficient:

- **k = 0:** No coupling (independent inductors)
- **k = 0.01-0.1:** Loose coupling (separate cores, some proximity)
- **k = 0.5-0.8:** Moderate coupling (shared core, separate windings)
- **k = 0.95-0.99:** Tight coupling (bifilar, interleaved windings)
- **k = 1:** Perfect coupling (theoretical ideal transformer)

Coupled Inductor Equivalent Circuit

Coupled inductors can be modeled as a transformer with leakage inductances:

```
Ideal Coupled Inductors:          Equivalent T-Model:

    L₁          L₂                   L₁(1-k)    L₂(1-k)
○───UUUU───●───UUUU───○          ○───UUUU──●──UUUU───○
```

```
         |                          |
     M (mutual)                 k√(L₁L₂)
                                   |
                                  _|_
```

T-Model Components

Component	Formula	Represents
L_{leak1}	$L_1(1-k)$	Primary leakage inductance
L_{leak2}	$L_2(1-k)$	Secondary leakage inductance
L_m	$k\sqrt{(L_1L_2)}$	Magnetizing inductance

Effect on VIC Circuit Behavior

Resonant Frequency Shifts

Coupling changes the effective inductances seen by each resonant tank:

Without Coupling (k=0):

```
f?,pri = 1/(2??(L?C?))
f?,sec = 1/(2??(L?C_wfc))
```

With Coupling:

The system has two coupled resonant modes. The frequencies split into:

```
f?, f? = function of L?, L?, C?, C_wfc, and k
```

Exact formulas are complex—use simulation for accurate prediction.

Mode Splitting

Coupled resonators exhibit "mode splitting"—two distinct resonant frequencies instead of one:

```
Uncoupled (k=0):            Coupled (k>0):

Response                    Response
    |                           |
    |    /\                     |   /\    /\
    |   /  \                    |  /  \  /  \
```

```
     |   /    \                     | /    \/    \
     └──────────────→ f             └──────────────→ f
          f₀                             f₁     f₂

  Single resonance              Split into two modes
```

Mode Splitting (equal resonators):

When $f_{0,pri} = f_{0,sec} = f_0$:

```
f? ? f? / ?(1+k) (lower mode)
f? ? f? / ?(1-k) (upper mode)
```

Separation increases with coupling coefficient k.

Energy Transfer

Coupling provides a path for energy transfer between primary and secondary:

Coupling	Energy Transfer	VIC Behavior
k = 0 (none)	Only through shared current path	Independent resonances
k = 0.1-0.3	Moderate magnetic coupling	Slight interaction
k = 0.5-0.8	Strong coupling	Significant mode splitting
k > 0.9	Very tight coupling	Behaves more like transformer

Bifilar Winding Coupling

Bifilar chokes have inherently high coupling ($k \approx 0.95\text{-}0.99$):

Effects of Bifilar Coupling:

- Large mode splitting
- Efficient energy transfer between windings

- Built-in inter-winding capacitance
- Lower overall SRF due to capacitance

Measuring Bifilar Coupling:

1. Measure $L_{series\text{-}aid}$ (windings in series, same polarity)
2. Measure $L_{series\text{-}opp}$ (windings in series, opposite polarity)
3. Calculate: $M = (L_{series\text{-}aid} - L_{series\text{-}opp}) / 4$
4. Calculate: $k = M / \sqrt{(L_1 \times L_2)}$

Stray Coupling

Even separate chokes may have unintended coupling if placed close together:

Configuration	Typical k	Mitigation
Toroids touching	0.01-0.05	Separate by >2× diameter
Air-core coils aligned	0.1-0.3	Orient perpendicular
Coils on same rod	0.5-0.9	Use separate cores

Design Considerations

When to Use Coupling:

- Compact design (bifilar combines L1 and L2)
- Intentional transformer action desired
- Specific mode-splitting behavior needed

When to Avoid Coupling:

- Independent tuning of primary and secondary needed
- Simpler analysis desired
- Want predictable single-resonance behavior

Layout Guidelines:

- Toroidal cores have low external field—good for isolation
- Orient coils perpendicular to minimize stray coupling
- Use shielding if isolation is critical
- Measure actual coupling to verify assumptions

Analyzing Coupled VIC Circuits

Coupled Circuit Analysis Steps:

> > 1. Measure or estimate coupling coefficient k
> > 2. Convert to T-equivalent model
> > 3. Analyze as three-inductor circuit
> > 4. Or use simulation with mutual inductance

Simulation Tip: When $k > 0.1$, coupled effects become significant. Always include coupling in simulation if windings share a core or are in close proximity.

VIC Matrix Calculator: The Choke Design module includes coupling coefficient input for bifilar windings. The simulation accounts for mutual inductance effects when analyzing coupled systems.

Next: Energy Efficiency Analysis →

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